D. An Integrated Surface Modification of Engineering Materials for Heavy Vehicle Applications

Stephen Hsu
National Institute of Standards and Technology
100 Bureau Drive, Gaithersburg, MD 20899
301-975-6120; fax: 301-975-5995; e-mail: stephen.hsu@nist.gov

Xaiolei Wang, Lewis K. Ives, Huan Zhang, Yanan Liang, Charles Ying
National Institute of Standards and Technology

DOE Technology Development Area Specialist: James J. Eberhardt
(202) 586-9837; fax: (202) 586-1600; e-mail: james.eberhardt@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

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Objectives

- Organize an international cooperative research program on an integrated surface modification technology under the auspices of the International Energy Agency (IEA).
- Design and identify surface features and patterns that can achieve friction reduction and enhanced durability for heavy-duty diesel engine components.
- Develop understanding and appropriate models to explain the effects of texturing on frictional characteristics. Develop appropriate thin films and coatings to achieve synergistic and complementary relationship with texturing to enhance performance.
- Discover and develop surface chemistry for protecting the films and coatings that work in synergy with the coatings.

Approach

- Determine the effects of the size, shape, pitch, and patterns of surface textural features on friction under (1) a high-speed, low-load regime; (2) a high-load, high-speed regime; and (3) a high-load, low-speed regime.
- Develop cost-effective fabrication technologies for creating surface textural features on various surfaces, including metals, ceramics, and coatings.
- Develop a test methodology to measure the effects of the textures on friction.
- Conduct research to develop an integrated system approach to combine the best practices in thin films, coatings, and surface chemistry for performances unrealizable by individual approaches alone.
- Concurrently, organize an international cooperative research program under the auspices of the IEA to pool resources and share this energy conservation technology worldwide.

Accomplishments

- Attended the IEA End Use Working Party meeting in Paris 2005 and presented the Implementing Agreement on Advanced Materials for Transportation (IA-AMT) end-of-term report. Based on input from the meeting, numerous revisions were made to incorporate new activities and future emphases.
- Won a 3-year extension of the IEA work from the Committee on Energy Research and Technology (CERT).
- Contacted potential participants in China, Australia, Finland, Japan, the United Kingdom, and Belgium to ask them to participate and to attend the Executive Committee meeting to be held in Porto, Portugal.
- Participated in a Special Symposium on Surface Texture in Porto in conjunction with the COST 532 conference.
- Demonstrated the geometric effects of various surface features under high-speed, low-load conditions and achieved significant friction reduction.
- Developed a new design principle incorporating a hydrodynamic wedge geometry inside the surface feature and achieved success in friction reduction, first on steel on soft metals (because of limitations of fabrication techniques).
- Overcame the fabrication limitation and demonstrated for the first time bearing steel on bearing steel under high-load, low-speed conditions (boundary lubrication conditions). Such surface texturing would yield a 30% reduction in friction in bench testing.
- Completed the initial development effort on an enhanced selective electrochemical etching technique in combination with photolithography on steel surfaces.
- Successfully demonstrated that cavitation played a role under high-speed, high-load conditions in a single dimple observation apparatus.
- Initiated an elasto-plastic lubrication model development effort to describe the friction reduction mechanism of surface textures under boundary lubrication conditions.

Future Direction

- Continue parametric study of the size, pattern, density, and L/D ratio in this uncharted territory.

Introduction

Frictional losses are inherent in most practical mechanical systems. The ability to control friction offers many opportunities to achieve energy conservation. Over the years, materials, lubricants, and surface modifications have been used to reduce friction in automotive and diesel engine applications to promote energy efficiency. However, in recent years, progress in friction reduction technology has slowed because much obvious inefficiency has been eliminated. A new avenue is needed.

Recently, laser-ablated dimples on surfaces have shown friction reduction properties and have been demonstrated successfully in conformal contacts, such as seals, where the speed is high and the load is low. The friction reduction mechanism in this regime appears to depend on the size, patterns, and density of dimples in the contact. The success of dimples in reducing friction has opened a new avenue for friction control for engine applications.

The objective of this project, therefore, is to explore the feasibility of surface texture designs to reduce frictional losses in energy transmission components, cylinder liner ring contacts, cam and lifters, and overhead bearing components. To ensure that the durability criteria are met, the texture patterns must be protected by thin films/coatings and appropriate lubricating chemistry over a broad range of operating conditions. The final outcome of the project will be to develop design principles and guidelines for various engine components under a wide range of operating conditions. To achieve maximum energy conservation, this technology should be implemented worldwide through international avenues for cooperation such as the IEA IA-AMT. Therefore, concomitant international cooperative research under IEA auspices is being conducted to pool resources from various countries to accelerate this technology development. Toward this end, the United Kingdom, China, Australia, Finland, Sweden, Israel, and Japan have agreed to participate under IEA annex IV on surface technology.

Approach

Previously, experiments were conducted to examine various surface textures on steel surfaces using photolithography and chemical etching. Using the same area coverage (percentage of area occupied by the surface textural features), surface features such as grooves, triangles, ellipses, and circles were compared under high-speed, low-load conditions similar to the operating conditions for seals. Results suggested that (1) surface texture size and shape had significant influence on friction, (2) orientation of the surface features with respect to the sliding direction changed the friction; and (3) the primary effect of surface textures is to accelerate the transition into a hydrodynamic lubrication regime. What is the fundamental friction reduction mechanism in this regime is still not clearly understood.

From an energy conservation point of view, most parasitic losses take place under high-load, medium- to low-speed conditions. Therefore, we need to extend this concept to increasingly severe contact conditions. However, when we ran the same surface texture patterns under boundary lubrication conditions, friction increased. A collaborative effort with Northwestern University using a sophisticated elastohydrodynamic friction model confirmed our experimental observations. Basically, under boundary lubricated conditions (high-load, low-speed), the edge stresses around the dimple increase frictional losses as if the surface is much rougher. So there is a trade-off in this regime.

Technical Highlights

During the past year, we developed a new surface textural feature with an inclined plane at the bottom of the feature to artificially generate a hydrodynamic wedge effect under plastic deformation loading; we called this the elasto-plastic lubrication model. Experiments conducted demonstrated significant friction reductions for steel on brass, aluminum, copper, and steel under boundary lubricated conditions.

When we used hard metals such as 52100 steel, the initial high contact pressure caused severe wear, damaging the surface textures; and the friction reduction results were erratic. To overcome this issue, we developed a wear-in procedure to create a smooth crater surface approximately 0.5 mm in diameter and then carved the texture onto the surface inside the crater with a diamond tip on the triboindenter. This way, a controlled interface was created to avoid severe wear-in and destruction of the surface features. We demonstrated that friction in a 52100 steel/52100 steel contact could be reduced significantly from 0.09 to 0.06.

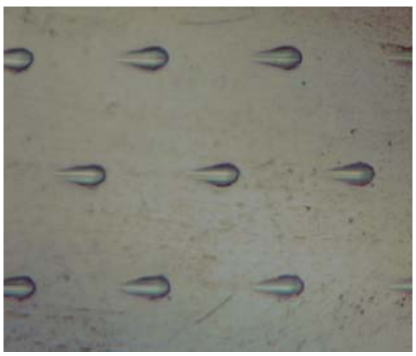
We also focused on developing a low-cost, rapid fabrication method and conducted tests to verify the friction reduction characteristics of the new fabrication technique. We used a microlithography/ chemical etching process previously to fabricate dimples with depths ranging from 3 to 10 μm. For shallow dimples, we needed to control the etching process precisely. Numerous factors could affect the electrochemical etching process, including the kind of electrolyte, the voltage, and the composition of the material. Since electricity always passed through the high-conductivity points, an inhomogeneous oxidation rate on a heterogeneous work piece will make the etching process selective. This was critical when a shallow depth was needed. A special electrolyte composed with acids was used for this purpose. Acid was effective in removing the oxidant on the surface so that etching could start quickly and uniformly. A circular dimple pattern was produced by this technique. A four-ball wear tester was used to carry out the friction tests using a ball-on-three flat configuration. The results showed that friction reduction of up to 32% has been achieved by the texture generated by this fabrication technique. Compared with previous textures generated by nanoscratching with sloped bottoms, the friction reduction was not as high (40–80%).

L/D Ratio and Size Effects

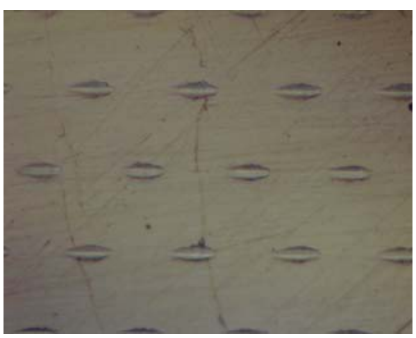
One of the critical issues in fabricating the new surface features was the effect of the slope at the bottom of the feature. In bearing applications, this typically was called the L/D ratio (bearing length over radius of the bearing) to estimate the lift force. We borrowed this concept and applied it to our design in terms of the length over the depth of the slope fabricated at the bottom of the surface features.

Another important factor was the size of the surface feature over the contact area. In boundary lubrication conditions, the edges of the surface features served as rough spots, increasing the friction; therefore, the optimum number of the features might be much smaller than for the high-speed, low-load regime. So we decided to conduct a series of experiments to investigate this effect.

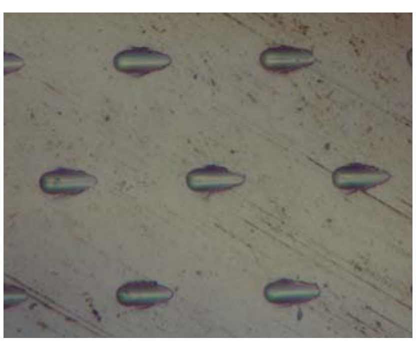
We fabricated several surface features by varying the L/D ratios and the sizes of the surface features. We ended with three patterns, A3, B2, and C4. The micrographs are shown in Figure 1. The densities of the three patterns are kept at 5%. Pattern A has a reversed wedge; pattern B has a symmetrical wedge, and pattern C has the classic wedge design orientation.



A3



B2



C4

Figure. 1. Three wedge orientation patterns for testing.

Figure 2 shows that the classical wedge orientation has the highest friction reduction capacity, reducing the average friction coefficient of the untextured pattern (UNT) from 0.09 to about 0.05, a 44% decrease in a 52100 bearing steel on 52100 bearing steel contact. Another significant point is that the friction starts at 0.09, which is at the low end of the boundary lubrication regime; the surface texturing features lower it to the hydrodynamic lubrication regime even though the contact is still operating at the boundary lubrication regime, as evidenced by the wear of the contact.

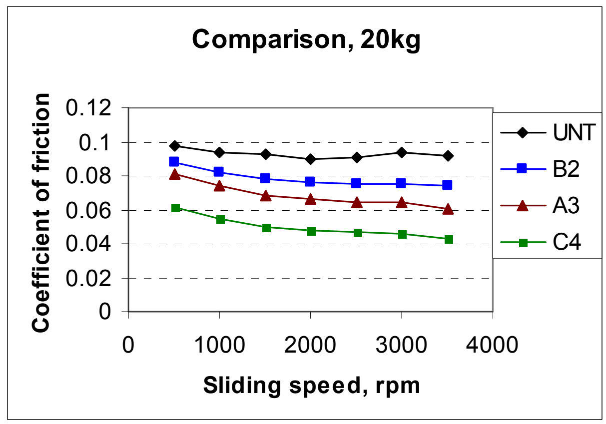


Figure 2. Comparison of friction coefficients of the three patterns under boundary lubrication conditions.

IEA Highlights

We attended the IEA End-Use Working Party (EUWP) meeting in Paris on April 18–19, 2005, and presented the IA-AMT end-of-term report. Based on input from the meeting, numerous revisions were made to incorporate new activities and future emphases. The EUWP voted to recommend a 4-year extension of the IEA work to CERT. CERT voted in June to give tentative approval for a 3-year extension, but it was noted that CERT wishes to see rapid progress on implementing the changes.

Potential participants in China, Australia, Finland, Japan, the United Kingdom, and Belgium were contacted to ask them to participate and to attend the IEA Executive Committee meeting to be held in Porto, Portugal, in conjunction with the COST 532 (European Cooperative Research Consortium on Triboscience and Tribotechnology) technical conference. The Executive Committee was successfully convened in Porto with delegates from China, the United Kingdom, Australia, Finland, Japan, Belgium, Portugal, and the United States. Annex 2 was successfully concluded; annexes 3 and 4 are continuing. We discussed two new activities in coatings and nanomaterials. The delegates will take the information and seek their governments' approval for formal participation in IA-AMT. The next meeting was scheduled for Calgary, Canada, for May 7–12, 2006, in conjunction with the Society of Tribologists and Lubrication Engineers (STLE)) meeting.

A Special Symposium on Surface Texture was held in Porto in conjunction with the COST 532 conference on October 12–15, 2005. The symposium featured speakers from eight countries—representing academia, industry, and government laboratories—who described their latest results in surface texturing in controlling friction.

Future Direction

We will continue our parametric study of size, pattern, density, and L/D ratio in this uncharted territory. Until we understand the basic operating mechanism and the effects of the operating parameters on the mechanism, we will not be able to develop design guidelines.

Presentations and Publications

S. M. Hsu, "Surface Texturing under Boundary Lubrication for Friction Control," Society of Tribologists and Lubrication Engineers annual meeting, Toronto, Canada, May 17–20, 2004.

Jorn Larson Basse, X. Wang, L. Ives, and S. M. Hsu, "Some Friction Experiments with Dimpled Surface Texture," Fourth China International Symposium on Tribology, Xian, China, November 8–11, 2004.

S. M. Hsu, "An Integrated Surface Texture Technology for Friction Control in Engine Components," DOE DEER Conference, San Diego, August 30–September 2, 2004.

S. M. Hsu, "Surface Texturing to Reduce Friction in Engine Components and IEA Program," COST 532 management meeting, Ghent, Belgium, October 17, 2004.

S. M. Hsu, "An Integrated Surface Modification Technique to Control Friction: A New Paradigm," Keynote speech at the Fourth China International Symposium on Tribology, Xian, China, November 8–11, 2004.

Y. Chae, X. Wang, and S. M. Hsu, "The Size Effect of Surface Texture on Lubricated Friction," First International Conference on Advanced Tribology, Singapore, December 1–3, 2004.

Jorn Larson Basse, Lew Ives, and S. M. Hsu, "Lubricated Friction Experiments with Coarse Groove Texture," Society of Tribologists and Lubrication Engineers annual meeting, Las Vegas, May 15–19, 2005.

S. M. Hsu and Xiaoli Wang," Surface Texturing for Friction Control," Society of Tribologists and Lubrication Engineers annual meeting, Las Vegas, May 15–19, 2005.

S. M. Hsu, "Surface Texturing: A New Design Principle for Friction Control under Boundary Lubricated Conditions," International Tribology Congress, Kobe, Japan, May 29–June 2, 2005.

S. M. Hsu, "Surface Texturing: Comparison of Various Geometric Shapes on Friction under High-speed Low-load Conditions," International Tribology Congress, Kobe, Japan, May 29–June 2, 2005.

S. M. Hsu, "An Integrated Surface Modification Technology: Project Review," DOE project review, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 13–15, 2005.

S. M. Hsu, "Integrated Surface Modification Technology: A Progress Report," COST 532 Symposium on Surface Textures, Porto, Portugal, October 12, 2005.

Jorn Larson Basse, X. Wang, L. Ives, and S. M. Hsu, "Some Friction Experiments with Textured Surfaces," in *Proceedings of Nordic Symposium on Tribology*, Troms, Norway, June 2004.

X. Wang, S. M. Hsu, "An Integrated Surface Modification Technique to Control Friction: A New Paradigm," in *Proceedings of the Fourth China International Symposium on Tribology*, Xian, China, November 8–11, 2004.

X. Wang and S. M. Hsu, "Surface Texturing: Comparison of Various Geometric Shapes on Friction under High-Speed Low-Load Conditions," in *Proceedings of the International Tribology Conference*, Kobe, Japan, May 29–June 2, 2005

X. Wang and S. M. Hsu, "Surface Texturing: A New Design Principle for Friction Reduction Under Boundary Lubrication Conditions," in *Proceedings of the International Tribology Conference*, Kobe, Japan, May 29–June 2, 2005.